THE CLIC APPROACH TO LINEAR COLLIDERS

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Abstract  A description is given of the two-beam method that is at the basis of the present CLIC effort. Progress has been made the last year in the understanding of wakefield effects and the resulting tolerances in the design of the rf structures and in the final focus design. So far, the aim of arriving at a consistent and well-understood design for a 1 TeV + 1 TeV collider has not been reached entirely. However, a reasonable hope still exists and our efforts continue.

INTRODUCTION

The name CLIC (CERN Linear Collider) originally referred to an advisory subpanel of CERN's long range planning committee in the years 1985-87. CLIC (presided by K. Johnsen) dealt with linear electron-positron colliders in the TeV range, trying to survey the field and arrive at some understanding of future possibilities. The results of this work were published in a formal report\(^1\).

Although this panel was dissolved, the studies (which had mobilised many individuals at CERN on a part-time basis) were continued under the leadership of W. Schnell, a small budget was obtained and the name CLIC now covers these activities, carried out by a varying number of people, not all from CERN, and most of whom also have other responsibilities.

As a start, we considered, somewhat arbitrarily, a design energy of 1 TeV per beam. The idea behind this was to reach approximately the same energy region as the SSC for constituent interactions. This parameter influenced the design in many ways. So far, we have stuck to it, even though it is becoming clear that it presents many problems.

Other similar studies (KEK, Novosibirsk, SLAC) are aiming at energies 2 to 5 times lower. Even under these conditions, the usual choice of a microwave linac fed by many separate power sources begins to look uninviting because of the very large number of sources needed. For CLIC, with its peak power of several TW, this approach seems out of the question. For this reason, most of the work by far is nowadays concentrated on a two-beam scheme proposed in 1986 by W. Schnell\(^2\), where all klystrons have been combined around a single, low-energy drive
beam. This scheme differs from the two-beam scheme proposed by Sessler et al. in that we plan to use travelling-wave structures instead of FEL's to generate the rf power, and superconducting cavities instead of induction linacs to accelerate the drive beam.

LUMINOSITY, DISRUPTION AND BEAM RADIATION

The interaction cross-sections scale roughly as $1/E^2$. This leads to high luminosity, which causes the main problems, rather than the high energy by itself.

The luminosity is limited by two effects: disruption and beam radiation, sometimes called "beamstrahlung". These depend on the various beam parameters in different ways and both effects together constrain the design in important ways.

Two extreme regimes of beam radiation exist: the classical and the quantum regime. In the first, the beam parameters are such that the typical photon energy, derived in a classical way, is less than the electron energy. If this is not the case, a quantum-mechanical approach is needed. The radiated power then depends on the beam parameters in a different way; and the more we get into this regime, the smaller the effect will be. Unfortunately it turns out that extremely short bunches, beyond present possibilities, are then needed. Moreover, coherent pair production at the final focus then becomes prohibitive. Most present-day designs and especially the CLIC one are therefore working in the wide transition region between the classical and quantum regimes.

In this region, the repetition rate turns out to vary inversely with the beam's aspect ratio at the collision point, without depending significantly on other parameters. We have chosen an aspect ratio $R=5$; larger values would lead to a vertical beam size even smaller than the 12 nm of the present design. This leads to a repetition rate $f_0$ of 1700 Hz. The beam power is proportional to $f_0 E_0/\omega$ where $E_0$ is the acceleration gradient and $\omega/2\pi$ the rf frequency. Thus, we have chosen a "moderate" gradient of 80 MV/m and set the frequency as high as we dared (29 GHz). At this frequency, fabrication problems (micron precision) and wakefield effects seem just manageable, but the situation is far from comfortable. The total mains power with these parameters will be about 200 MW.

MAIN CLIC PARAMETERS

The main CLIC parameters are as indicated in Table I.

Many of these parameters are close to practical limits. The luminosity should not be much lower (in fact, we would prefer $10^{34}$ cm$^{-2}$s$^{-1}$).
The focus aspect ratio cannot be much increased without reducing even further the extremely small beam height required. The fractional energy loss by beam radiation should certainly not be any higher and increasing the pinch-enhancement might be very difficult. The rf frequency is uncomfortably high. However, relaxing any of these parameters would lead to even higher beam power and RF power.

It would be very attractive to accelerate several bunches per pulse. This could be done by injecting the first bunch when the accelerating structure is not yet entirely filled. Successive bunches would see a more completely filled structure; this would balance the gradient decrease caused by beam loading from the preceding bunches. A power extraction efficiency of 30% might be reached but multi-bunch wakefield effects might not allow the scheme to work.
SUPPLYING THE RF POWER - THE CLIC TWO-BEAM APPROACH

The solution proposed is to combine all klystrons into a single high-intensity electron beam (drive linac) running in parallel with the main linac (Fig. 1).

This beam is accelerated by superconducting cavities filling only a fraction of its length and the beam energy is transmitted to so-called transfer structures that feed the main linac at 29 GHz. The superconducting cavities work at a much lower frequency (350 MHz) and with a much lower average field strength (6 MeV/m over the cavity length) than the main linac (80 MeV/m).

To make the various transfers of energy possible, each pulse of the drive beam contains a number of bunches (actually 4) at 350 MHz and each of these will be subdivided into 10 bunchlets at 29 GHz. The drive beam must have an energy of a few GeV to avoid phase slippage with respect to the main linac. Of course, the total charge per pulse must be much higher in the drive linac than in the main one, since the gradient is lower and energy is conserved.

The transfer structures have a filling (or rather emptying) time of one 350 MHz period, so that the first bunchlet of each 350 MHz bunch will see an empty structure. Each successive bunchlet will see a higher decelerating gradient as the transfer structures charge up. However, the acceleration by the superconducting cavities will also increase, since the bunches will pass these on the rising slope of the sine wave (Fig. 2). These two slopes can be made to balance.

The main linac’s structures will have a longer filling time, corresponding to the total duration of the drive linac’s bunch train.

It turns out that the ratio of the accelerating gradients of main linac and drive linac scales with the frequency ratio. (Some other factors, such as the fraction of the drive linac occupied by superconducting cavities, also play a role). This makes the 350 MHz drive frequency near-optimum. As it happens, CERN has developed such cavities for LEP. Their cost will have to be reduced for use in CLIC, but otherwise they are just right.

To obtain the relatively low deceleration of the drive beam
together with a large energy transfer, the transfer structures must have a low impedance (a few hundred times less than the main linac's structures). They will thus have a large aperture which helps to avoid problems with the intense drive beam such as transverse wakefield effects. The losses in these structures also turn out to be low (90% efficiency).

It would, in principle, be possible not to dissipate the power at the end of the main linac's sections in terminating resistors, but to feed it back to the next transfer structure of the driving linac, which could then accelerate additional bunchlets injected at the correct phase. These might in turn give back their gained energy to the superconducting cavities. In this way, the efficiency might perhaps be increased by a factor 2.

The main problem with the drive linac will be to generate the short, intense bunchlets. The emittance need not be small, and in principle we could imagine to combine a number of SLC-like beams in transverse phase space. However, a more elegant solution may well be found. Some preliminary work on a possible test facility has been done by Y. Baconnier and colleagues, but this is still at a very early stage.

Typical parameters for the drive linac are given in Table II.

In the following sections, I shall describe some of the detailed work that has been done lately on various aspects of this scheme.

**WAKEFIELD EFFECTS AND RF FOCUSING**

The presently assumed normalised emittances are $3 \times 10^{-6}$ m horizontally and $10^{-6}$ m vertically. There seems little doubt that this can be obtained by damping rings; several tentative designs are available.
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<th>TABLE II Drive linac parameters.</th>
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<td>Fraction of main linac active length occupied by drive linac</td>
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<td>Drive linac active length</td>
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Great care will be needed to conserve the emittance during ejection and especially during the acceleration to full energy. The latter problem has been studied in considerable detail\(^9\)\(^-\)\(^10\) and is now believed to be reasonably well understood. The two main effects that may lead to emittance increase are:

a) Chromatic smearing. Misalignments lead to coherent betatron oscillations. These do not stay coherent for very long because of the chromatic betatron frequency spread. Once the coherence is lost, correction is no longer possible.

b) Transverse wakefields and the resultant beam break-up. The wakefields from the head of the bunch excite the following particles in resonance.

Detailed study has shown that earlier calculations assuming constant focusing were too optimistic by an order of magnitude; AG focusing apparently increases the wakefield effect. Introduction of BNS damping\(^11\) by means of energy spread is insufficient.

A better solution appears to be the use of radio-frequency focusing obtained by using slits instead of round apertures in some of the irises. This method, first proposed by R. Palmer and analysed in detail by Schnell\(^12\) and Henke\(^13\) is interesting because the focusing effect scales both with frequency and with accelerating gradient and thus becomes appreciable in the present application.

The damping appears strong enough to remove both effects a) and b) and the energy spread may now be minimised, as required for the final
focus (chromatic aberration). With the assumed emittances the alignment tolerances will be 10 \mu m for the rf structures and 1 \mu m for quadrupoles. Detection of the beam position to within 1 \mu m will be required. Beam monitors that should allow this have been studied 14-15.

With the present design, most of the focusing will be done with conventional quadrupoles; the rf quadrupoles will just cause the tune spread between the head and the tail of the bunch, without changing the central tune.

Numerical studies of slotted-iris structures16 have shown that earlier rough estimates of their performance were correct within 15%.

WAKEFIELDS IN THE DRIVE LINAC

Study of the wakefield effects has started17. It has appeared that the longitudinal effects of cross-section changes along the line may be important and that such changes will have to be minimized. In the superconducting cavities the longitudinal wakefield may also be harmful, as it will change the linear voltage increase for successive bunchlets.

In the transfer structures the resistive wall impedance of the smooth sidewalls may cause beam break-up; to suppress this, either an energy spread of 5% over the entire bunch train will be needed, or the aperture of the structure will have to be increased.

TRANSFER STRUCTURES

Model tests have been made on scaled-up (2 GHz) models of the low-impedance transfer structure. Properties of a 4-cell and later a 12-cell model (Fig. 3) were measured18-20, such as dispersion curves and coupling impedance.

FIGURE 3 Test model (2 GHz) for a transfer structure with its cover taken off
The structure is a rectangular waveguide with teeth far away from the beam to obtain the required low impedance. The teeth do not extend across the full width of the guide so that adjacent cells couple both electrically and magnetically.

The model measurements are encouraging: the impedance, the group velocity and the efficiency of energy transfer to the fundamental mode \((\pi/2)\) seem about right. Further optimisation is now being done by computer modelling, using the MAFIA codes developed by Weiland at DESY.

**MAIN LINAC STRUCTURES**

Tests on different geometries for the main linac structures and calculation have shown that it is difficult to find a better structure than the classical disc-loaded waveguide. This has therefore been adopted for further study. The centre hole has to be relatively large compared to existing linacs to minimize wakefield effects and to obtain a high group velocity; this is necessary to keep the section length reasonable. Despite the short wavelength, the tolerances (mainly because of the high group velocity) turn out to be reasonable \((\pm 3 \mu m)\).

A complication is the provision of longitudinal slots in the structure's sidewalls, foreseen (following a suggestion by R. Palmer) to increase the dissipation of undesired transverse modes. This might make the use of multiple bunches possible. The slots would be somewhat longer than the inter-iris distance and would therefore have to cut through the irises.

Many different fabrication methods for the 25 cm long, 9 mm outer diameter sections have been considered, but it is too early to make a choice among them. The large number (~100'000) of structures to be manufactured means that a very careful consideration of all details is essential. A first series of precision-machined cups (Fig. 4) has been made and measurements (so far without brazing) have started\(^2\).

The structures proper will have to be embedded into a larger diameter cylinder provided with longitudinal and transverse holes for vacuum and water cooling, and for feeding in and out the power. Beam position monitors will have to be included in the structures.

Calculations of the dissipation show that the maximum average temperature increase on the copper surface will be only 1.9°C. Slightly more worrying is the instantaneous increase of 50°C during each 11 ns pulse and it still has to be shown that this is acceptable from the fatigue point of view.

**FINAL FOCUS**

The very small beam height at the focus given in Table I was postulated in order to have an acceptable beam power, at a stage where no corre-
This still does not quite exist, and it may therefore be said that we have no consistent set of parameters. Nevertheless much work is being done in this area and it is hoped that a satisfactory solution may be found.

The most important problem is chromatic aberration. Using telescope optics for demagnification, designs may be found that minimise the chromatic effects but the remaining aberration is still too high.

Better results have been found by using bending magnets and sextupoles, as was done at SLC. This allows correction of the first-order chromatic terms; but at least for present designs the higher-order aberrations (both chromatic and geometric) remain somewhat too high. In addition, the quantum fluctuations in radiation loss, caused by the bending magnets and the final quadrupole (Oide effect) will cause an increase of final beam height that is still unacceptable in present designs. The specified luminosity could be reached by reducing the emittances by a factor 2; this would make the alignment more critical.

A final energy spread of ±0.4% was assumed for these studies. To obtain this with an energy extraction of 5% from the main linac will require a reduction of the "natural" energy spread caused by beam loading by an order of magnitude. This may be possible, but it has not been proven conclusively.
CONCLUSION

In spite of the low level of funding and the fact that nearly all work is done on a part-time basis with strong competition from the LEP commissioning programme, some interesting progress has been made during the past years. The main point has been the better understanding of the beam break-up effect and its suppression by RF focusing. Some hardware tests and calculations on models of the transfer structure have increased our confidence in this unusual component. Studies on the main structures and their fabrication are just starting. Some damping ring designs now exist that nearly promise the required performance and it is thought that some further improvement may be possible. Lastly, the final focus design is improving, although the nominal performance specification has not yet been met. It may be possible that multi-bunch operation will be one way of solving some of the outstanding problems. It is hoped that during the coming years a better-understood, consistent design for a 1 TeV + 1 TeV collider will emerge.

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